SCIENCE FOR GLASS PRODUCTION

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GLASS HARDENING USING THE CRITICAL AIR FLOW

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A method for design of a compressor – receiver – hardening diffuser system with a one-time pressure drop is described. The good prospects for using such systems in the theory and practice of sheet glass hardening are demonstrated.

Air-jet hardening of sheet glass prevails in the industry. At the same time, intensification of this process to a large extent is hampered by the need to ensure high air pressure in hardening diffusers (45 – 50 kPa) with a fan output up to 100 thousand m^3/h. Domestic machine builders do not produce such fans.

It is established [1] that the intensity of heat exchange with the chilling medium, which is estimated on the basis of the heat transfer coefficient, is a function of the so-called "shock" velocity of an air jet v_a, which, in turn, depends on the velocity of an air jet flowing out from the nozzle of the hardening diffuser.

In this context, glass hardening using a critical air flow appears promising. The general scheme of this method can be implemented in the "compressor – receiver – hardening grates" chain; however, solving this problem is complicated by the absence of a method for the calculation of such systems. The present study is dedicated to a partial solution of this problem.

Thus, there is an enclosed vessel (a receiver) *1* of volume V filled with air at a pressure $p(0)$ (Fig. 1). The other parameters of the air inside the receiver are easy to calculate [2]:

mass

$$m(0) = \frac{m(0)VM}{RT};$$

density

$$\rho = \frac{m(0)}{V},$$

where $M = 29.0$ kg/kmole, $R = 8314$ J/(kmole · K), and $T = 293$ K.

At the moment of abrupt opening of the valve *2*, the air flows from an opening with surface area S into the ambient medium with the parameters $p = p_{atm} = 10^5$ Pa and $T = 293$ K. The outflow is adiabatic; therefore, it is possible in principle to construct its characteristics:

$$p = f_1(\tau);$$

$$v = f_2(\tau),$$

where τ is the process duration; v is the outflow rate.

According to A. D. Al'tshul' [3], two modes of outflow are possible. If $p_{atm}/p \le 0.53$, this is the critical mode that proceeds at a constant outflow rate

$$v_{cr} = c = \sqrt{k\frac{p_{atm}}{\rho_{atm}}}, \quad (1)$$

where c is the velocity of the propagation of sound in atmospheric conditions; $k = 1.405$ is the adiabatic index.

In this case, the mass flow rate of air

$$M_a = M_{max} = \psi_{max} S\sqrt{p\rho}, \quad (2)$$

where $\psi_{max} = 0.685$.

If $p_{atm}/p \ge 0.53$, the outflow is subcritical, the flow rate is

$$v = \sqrt{2\frac{k}{k-1}\frac{p}{\rho}\left(1-\left(\frac{p_{atm}}{p}\right)^{\frac{k-1}{k}}\right)} \quad (3)$$

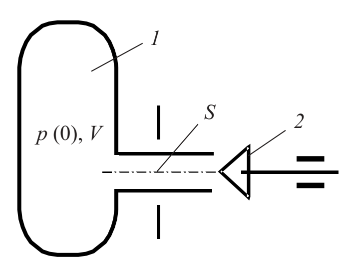

Fig. 1. Calculation scheme.

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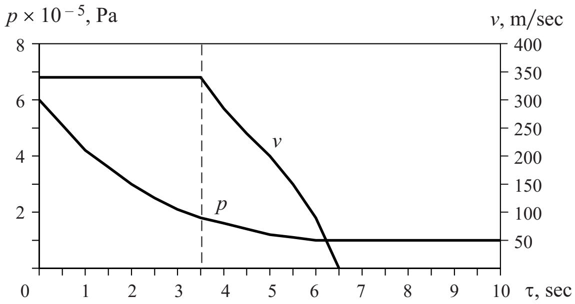

Fig. 2. Characteristics of air flowing from a receiver.

and the mass of the flow rate is

$$M_a = \mu S \sqrt{2\frac{k}{k-1} p\rho \left(\left(\frac{p_{atm}}{p} \right)^{\frac{2}{k}} - \left(\frac{p_{atm}}{p} \right)^{\frac{k+1}{k}} \right)}, \qquad (4)$$

where μ is the outflow coefficient.

By correlating formulas (3) and (4), we obtain

$$M_a = \mu S v \rho \sqrt{\left(\frac{p_{atm}}{p} \right)^{\frac{2}{k}}}. \qquad (5)$$

Since the pressure inside the receiver keeps decreasing, we propose a variant of discrete calculation of the flow parameters. We will split the flow process into small time intervals $\Delta\tau$, within which the pressure in the receiver cab be assumed to remain constant. In this case, the algorithm for calculations is as follows.

In the initial state at $\tau = 0$: $p = p(0)$, $m = m(0)$, $\rho = \rho(0)$, i.e., all parameters are known.

In the first step ($\tau_1 = \Delta\tau$) we will determine the mode of a quasi-stationary outflow based on the absolute value of the ratio p_{atm}/p.

If the regime is critical, v_1 and M_{a1} are estimated from formulas (1) and (2), and for a subcritical regime these parameters are calculated according to formulas (3) and (5), and after that we will consecutively determine the following parameters:

the mass of the air that has left the receiver

$$\Delta m_1 = M_{a1}\,\Delta\tau;$$

the mass of the air remaining inside the vessel

$$m_1 = m(0) - \Delta m_1;$$

the air density in the vessel

$$\rho_1 = m_1/V;$$

and the air pressure in the vessel

$$p_1 = \frac{\rho_1 RT}{M}.$$

For any ith step of the calculation, we determine the process duration $\tau_i = i\Delta\tau$, and identify the flow regime from the ratio p_{atm}/p.

In the case of a critical regime:

$$v_i = c = \sqrt{k\frac{p_{atm}}{\rho_{atm}}};$$

$$M_{ai} = \psi_{max} S \sqrt{p_{i-1}\rho_{i-1}}.$$

In subcritical regimes

$$v_i = \sqrt{2\frac{k}{k-1}\frac{p_{i-1}}{\rho_{i-1}}\left(1 - \left(\frac{p_{atm}}{p_{i-1}}\right)^{\frac{k-1}{k}}\right)};$$

$$M_{ai} = \mu S v_i \rho_{i-1} \sqrt{\left(\frac{p_{atm}}{p_{i-1}}\right)^{\frac{2}{k}}}.$$

Consequently,

$$\Delta m_i = M_{ai}\,\Delta\tau; \quad m_i = m_{i-1} - \Delta m_i;$$

$$\rho_i = m_i/V; \quad p_i = \frac{\rho_i RT}{M}.$$

The calculations continue in this way until the air finally leaves the receiver at $p_i = p_{atm}$.

We have studied the particular conditions of air flowing from a receiver of volume 10 m^3 with initial pressure 600 kPa via an opening, whose cross-sectional area was identical to the cross-sectional area of the exit nozzles of the vertical hardening plant (Fig. 2).

As can be seen, for the given design and technological parameters of the system the duration of the critical air outflow is equal to 3.5 sec. Within this interval, the flow rate is constant and amounts to about 340 m/sec, and the air pressure constantly decreases from 600 to 180 kPa. After that the pressure declines rather gradually and the outflow velocity drops abruptly. By the moment $\tau = 6.6$ sec the receiver is totally emptied.

The preliminary calculations indicated that the heat transfer coefficient under the critical flow can reach 700 W/(m^2 · K) and even more, which could be previously attained only in the conditions of liquid hardening.

Thus, the use of the critical air flow is of special significance for the theory and practice of sheet glass hardening.

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